

# Security Constraints in Temporal Role-Based Access-Controlled Workflows (Extended Version)\*

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## Abstract

Workflows and role-based access control models need to be suitably merged, in order to allow users to perform processes in a correct way, according to the given data access policies and the temporal constraints. Given a mapping between workflow models and simple temporal networks with uncertainty, we discuss a mapping between role temporalities and simple temporal networks, and how to connect the two resulting networks to make explicit *who can do what, when*. If the connected network is still executable, we show how to compute the set of authorized users for each task. Finally, we define security constraints (to prevent users from doing unauthorized actions) and security constraint propagation rules (to propagate security constraints at runtime). We also provide an algorithm to check whether a set of propagation rules is safe, and we extend an existing execution algorithm to take into account these new security aspects.

**Keywords:** Access-controlled workflow, TRBAC, temporal separation of duties, security constraint propagation rules, STNU.

## 1 Introduction

**Context and motivation.** Workflow technology has emerged as a key technology to specify and manage business processes within complex organizations. Recent research has focused on the issues related to workflow temporalities, such as uncertain durations of tasks, temporal constraints between (even non consecutive) tasks, deadlines and so on [7]. As complex tasks need the suitable access to data and systems, *role-based access control (RBAC) models* play an important part as they both deal with the classical security analysis (concerning authorization inspection, administrative models, and hierarchies) and allow one to consider also temporal aspects [1, 3, 15, 22, 24].

Thus, in the business process context, RBAC models and workflow models need to be suitably merged, in order to allow users to perform processes in a correct way according to the given data access policies and the temporal constraints.

To properly manage temporal constraints of workflows, solutions have been proposed that are based on a mapping between workflow models and *simple temporal constraint networks with uncertainty (STNU)* [26] and that allow one to deal with *controllability* of workflow models. In a nutshell, an STNU, and its corresponding workflow, is *controllable* if it is always possible to

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execute the network without violating any constraint no matter what the uncertain durations (of tasks) turn out to be [26].

Even if both a temporal workflow model and a temporal access control model pass their security analyses successfully, in general we cannot be sure that their composition behaves as we expect. Hence, we need a way to analyze what happens when we put an access control model on top of a workflow model. As a temporal workflow can be translated into an equivalent STNU, if we were able to extend this network to take into consideration the security aspects, we could have some chances of reasoning on their interplay.

**Contributions.** In this direction, we have merged *temporal role-based access control (TRBAC)* and temporal workflow models to seamlessly manage temporal constraints when executing tasks together with possible temporal constraints related to the availability of agents able to execute tasks according to their roles. Thus, the first two contributions of this paper are: proposing a mapping of valid intervals of roles into an equivalent simple temporal network, and merging it with the STNU specifying the workflow model.

The enabling times of the roles in TRBAC models are usually specified according to periodic expressions using *calendars* [20]. We propose the concept of *configuration*, which corresponds to an STNU containing both the representation of a temporal workflow and the related role-based access model, considering periodic role-enabling intervals within a given, limited time window. A configuration allows us to check if the workflow is executable with respect to the access control model. That is, it allows us to understand if these two models are consistent with each other. If so, then we are able to compute which users belonging to which roles are authorized to execute the tasks.

Moreover, a further contribution is the definition of *security constraints (SCs)*, not directly expressible in role-based access models, along with their *security constraint propagation rules (SCPRs)*. The former are used to prevent users from doing unauthorized actions (e.g., starting/ending a task) if the current time satisfies the constraint itself, whereas the latter are used to propagate these security constraints depending on what is going on. If different users make different choices, then SCPRs will propagate different SCs. This *dynamic* approach reacts to observations of the occurring runtime events. As far as we know, this is the first attempt to use temporal networks to model (and enforce) security (policies).

**Organization.** Section 2 reviews essential background of simple temporal networks (STNs), STNUs, a mapping from workflow models to STNUs, and TRBAC. Section 3 provides a new mapping to translate the enabling intervals of roles of TRBAC into an STN and a connection mapping to connect the workflow STNU to the access control STN. It also shows how to derive the set of authorized users for each time point in these networks. Section 4 introduces a case study also specifying three security policies that are supposed to hold in that context. Section 5 defines SCs and SCPRs to enforce (temporal) security policies when executing a temporal workflow. It also discusses a safeness algorithm for a set of SCPRs. Section 6 discusses how to extend an already existing execution algorithm for STNUs so as to take into account these rules too. Section 7 discusses related work. Section 8 draws conclusions and discusses future work. The proofs of our results are given in the appendix.

## 2 Background

In this section, we briefly review the theoretical foundations of STNs [13] and STNUs [18], how to map a workflow into an STNU, and role based access models.

### 2.1 Simple Temporal Networks

**Definition 1** A *Simple Temporal Network (STN)* is a pair  $\langle \mathcal{T}, \mathcal{C} \rangle$ , where  $\mathcal{T}$  is a set of time points with continuous domain, and  $\mathcal{C}$  is a set of constraints of the form  $X - Y \leq k$  with  $X, Y$  time points and  $k \in \mathbb{R} \cup \{-\infty, \infty\}$  [13].

A *Simple Temporal Constraint Satisfaction problem (STCP)* is the problem of finding a complete assignment of values to the time points in  $\mathcal{T}$  satisfying all constraints in  $\mathcal{C}$  [13].

An STN can also be represented as a directed graph where each node represents a time point of  $\mathcal{T}$  and each edge  $X \xrightarrow{[x,y]} Y$  (called *requirement link* or *link*, for short) represents the two constraints  $Y - X \leq y$  and  $X - Y \leq -x$  belonging to  $\mathcal{C}$ . For each pair of time points in a directed graph representing an STN, there exists only one edge between them, which is labeled exactly by one range. We can also represent it through an equivalent directed weighted graph (called *distance graph*  $G_d$ ), where the set of nodes is still the set of time points and each constraint  $Y - X \leq k$  is mapped to a weighted edge  $X \xrightarrow{k} Y$ . That is, each edge of the STN  $X \xrightarrow{[x,y]} Y$  is mapped to  $X \xrightarrow{y} Y$  and  $Y \xrightarrow{-x} X$  in the distance graph.

To avoid confusion, hereinafter *edges* will refer to the edges in the distance graph, whereas (*requirement*) *links* will refer to the edges in the STN graph.

To find the ranges of distance values allowed between time points, one can run the *all pairs shortest paths algorithm* on the distance graph  $G_d$  [8]. If  $G_d$  contains a negative cycle, the given STP does not admit solutions, i.e., it is *inconsistent*. The upper bound of the range between the  $i^{\text{th}}$  time point and the origin time point  $Z$  corresponds to the shortest path from node  $Z$  to that node, whereas the lower bound corresponds to the negation of the shortest path in the opposite direction.

Assuming that the origin time point  $Z$  is the starting point, to find a complete solution  $S = \{Z = 0, X_1 = t_{X_1}, \dots\}$  for each time point  $X$ , we choose a value among those allowed in its range adding the link  $Z \xrightarrow{[x,x]} X$  to the STN (if a link  $Z \rightarrow X$  already exists in the STN graph, then we replace it with the new one). This translates into adding  $X - Z \leq x$  and  $Z - X \leq -x$  to  $\mathcal{C}$ , which fixes the value for  $X$ . To get the new updated ranges for the remaining time points, we *propagate* the effect of this assignment recomputing the shortest paths on the distance graph containing now the two new constraints  $Z \xrightarrow{x} X$  and  $X \xrightarrow{-x} Z$ . Managing in such way all time points, we obtain a complete solution.

## 2.2 STN with Uncertainty

**Definition 2** A *Simple Temporal Network with Uncertainty (STNU)* extends an STN by adding a set of contingent links [19]. Formally, an STNU is a triple  $S = \langle \mathcal{T}, \mathcal{C}, \mathcal{L} \rangle$  where:

- $\langle \mathcal{T}, \mathcal{C} \rangle$  is an STN,
- $\mathcal{L}$  is a set of *contingent links* of the form  $(A, x, y, C)$  (or, equivalently,  $A \xrightarrow{[x,y]} C$  in the STNU graph), where the *activation* point  $A$  and the *contingent* point  $C$  are different time points ( $A \neq C$ ),  $x$  and  $y$  are such that  $0 < x < y < \infty$ , and
  - for each  $(A, x, y, C) \in \mathcal{L}$ ,  $\mathcal{C}$  contains  $C - A \leq y$  and  $A - C \leq -x$ ,
  - if  $(A_1, x_1, y_1, C_1)$  and  $(A_2, x_2, y_2, C_2)$  are two distinct contingent links, then  $C_1 \neq C_2$ ,
  - the contingent time point of a contingent link may play the role of an activation point for another one.

When we are not interested in talking about the range of a link, we simply write  $A \Rightarrow C$  (for contingents) or  $X \rightarrow Y$  (for requirements) omitting  $[x, y]$ . As notation, we write  $A$  to refer to activation time points,  $C$  to contingent time points and  $X$  to generic time points. If  $X$  is not a contingent time point, then it is also called *control time point*.

It is easy to see that each STN  $\langle \mathcal{T}, \mathcal{C} \rangle$  is also an STNU  $\langle \mathcal{T}, \mathcal{C}, \mathcal{L} \rangle$  where  $\mathcal{L} = \emptyset$  (i.e., without contingent links).

When the network is being executed, the system incrementally assigns a fixed time value to each control time point (i.e., to each non-contingent time point) among those allowed in its range. The system can only *observe* the occurrence of any contingent  $C_i$ , which is not under the control of the system and is however guaranteed to occur in such a way that that  $C_i - A_i \in [x_i, y_i]$ .

The meaning of contingency can be thought as representing processes that are not under the control of the workflow systems and whose exact duration is unknown *but* bounded by the range  $[x, y]$ . For example, the writing of this paper once started (i.e., once  $A$  has been executed) will last at least a minimum amount of time  $x$  to allow authors to get a polished version to

be submitted and at most  $y$  ( $> x$ ), which in this context is related to the submission deadline. However, the exact moment when the authors will have it finished (and consequently the paper will have been submitted) is unknown at this stage.

In an STNU, we need to move from the concept of *consistency* to that of *controllability*, because we now have to deal with “uncertainty”, which is by definition out of our control. We must make sure that no execution will violate any constraint. Hence, an STNU is *controllable* if we are able to execute all control time points satisfying all constraints in  $\mathcal{C}$  no matter what the durations of the contingent links turn out to be. The rest of this section provides everything we need to define the various types of controllability (see [26] for details).

A *situation*  $\omega = (d_1, \dots, d_n)$  is defined by fixing a chosen duration for each contingent link. Fixing a situation is equivalent to transforming an STNU into an STN as each  $A_i \xrightarrow{[x_i, y_i]} C_i$  is replaced with  $A_i \xrightarrow{[d_i, d_i]} C_i$  ( $d_i \in [x_i, y_i]$ ). A *(situation) projection* is a mapping  $sitPrj : \langle \mathcal{T}, \mathcal{C}, \mathcal{L} \rangle \times \Omega \rightarrow \langle \mathcal{T}, \mathcal{C}' \rangle$ , which considers all contingent links as if they were requirement links with a fixed distance. Therefore, an STNU represents an infinite family of STNs (each one *projecting* a different situation). The *space of all situations* is represented by  $\Omega$ . A *schedule* is a mapping  $\psi : \mathcal{T} \rightarrow \mathbb{R}$  that assigns a real value to each time point. The *space of all schedules* (since an STNU can be executed in infinite ways) is represented by  $\Psi$ . An *execution strategy* for  $\mathcal{S}$  is a mapping  $\sigma : \Omega \rightarrow \Psi$  such that for each situation  $\omega \in \Omega$ ,  $\sigma(\omega)$  is a complete schedule for the time points in  $\mathcal{T}$ .

Three main kinds of controllability for STNUs have been originally defined in [26]. An STNU is *weakly controllable* if there exists a viable execution strategy, i.e., if every projection is consistent. An STNU is *strongly controllable* if there exists a set of viable execution strategies considering all possible projections, where each control time point is assigned the same value by the schedule in all the strategies. An STNU is *dynamically controllable* if there exists an execution strategy for  $\mathcal{S}$  that is both viable and dynamic\*, where an execution strategy is dynamic\* whenever: if the durations of all contingent time points executed before the next time point  $X$  are equal in all different situations  $\omega_1$  and  $\omega_2$ , then the schedule must assign the same value to  $X$  in both  $\omega_1$  and  $\omega_2$ .


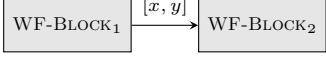
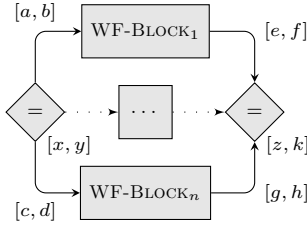
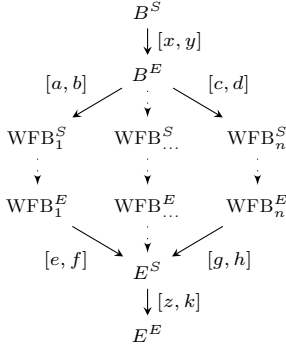
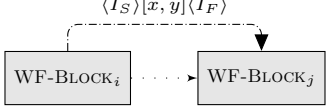
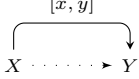
Checking the dynamic controllability of an STNU is polynomial. The first algorithm was proposed in [19] and further improvements were given in [16, 18]. The main idea behind the controllability check is that of restricting the execution strategies ruling out those that would squeeze the contingent links, where a contingent link is *squeezed* if the other constraints imply a tighter lower and/or upper bound for the link. Hereinafter, we will refer to the basic algorithm introduced in [18] for STNU dynamic controllability, avoiding the discussion related to subtle further optimizations. The algorithm takes as input a labeled distance graph built from the STNU according to the following mapping: each requirement link  $X \xrightarrow{[x, y]} Y$  is mapped to  $X \xrightarrow{y} Y$  and  $Y \xrightarrow{-x} X$  in the labeled distance graph. For each contingent link  $A \xrightarrow{[x, y]} C$ , we have the same edges  $A \xrightarrow{y} C$  and  $C \xrightarrow{-x} A$ , but we also have  $A \xrightarrow{c:x} C$  and  $C \xrightarrow{C:-y} A$  which are the *lower-case* and the *upper-case* edge, respectively.

The algorithm proposed in [18] iteratively checks if the *AllMax* projection (i.e., the projection in which all contingent links take their maximal duration) is consistent in the STN-sense, where the *AllMax* projection is the unlabeled distance graph obtained by deleting all lower-case edges and all labels from the upper-case edges (whenever we remove labels from edges or we add new edges, if an edge of the same type already exists in the graph we are operating on, then we usually keep that specifying the tighter constraint with respect to the type of edge). If so, it generates new edges according to suitable edge generation rules given in [18], until either quiescence (i.e., no further constraints are added or the existing ones are tightened) or the cutoff bound used to make the algorithm strongly polynomial, is reached. A detailed analysis of the execution of this algorithm as well as how the proposed rules work can be found in [18].

## 2.3 Workflow Modeling

A *workflow* consists of a set of tasks to be executed in some order to achieve some (business) goal(s). A *temporal workflow* extends the classical one by taking into account temporal con-

Table 1: Workflow to STNU mapping.

WORKFLOW BLOCK	CORRESPONDING STNU
	$A \xrightarrow{[x, y]} C$
	$WFB_1^E \xrightarrow{[x, y]} WFB_2^S$
<p><math>WFB_2^S</math> (resp., <math>WFB_1^E</math>) is a convention to represent the start (resp., the end) time point of the workflow block WF-BLOCK<sub>2</sub> (resp., WF-BLOCK<sub>1</sub>).</p>	
	
<p><math>B^S \rightarrow B^E</math> (resp., <math>E^S \rightarrow E^E</math>) is a convention to represent the branch (resp., join) component as an internal task.</p>	
	
<p><math>X</math> is either an activation point (if <math>\langle I_S \rangle \equiv S</math>) or a contingent point (if <math>\langle I_S \rangle \equiv E</math>) of some task inside WF-BLOCK<sub><math>i</math></sub> and <math>Y</math> is the same but with respect to WF-BLOCK<sub><math>j</math></sub>.</p>	

straints that typically require a lower and an upper bound on the duration of tasks. A temporal workflow also allows one to express relative constraints restricting the allowed time distance between the start or the end of two (not necessarily consecutive) tasks.

In this paper, we only consider *structured* workflows that can be described by a well-defined grammar and, without loss of generality, we do not consider alternative/choice/conditional paths. Thus, we will focus on the workflow specification where all the specified tasks have to be properly executed. An example of the basic constructs of this grammar is given in Table 1 (WORKFLOW BLOCKS), where, for each block, the equivalent STNU is depicted on the right of it (EQUIVALENT STNU).

The table shows the basic workflow block task (first row), which can be thought of as a terminal symbol, and then the sequence (second row) and parallel (third row), which can be thought of as non-terminal symbols. The last component (relative constraint) in the fourth row only imposes further temporal constraints between the start/end of two tasks and it has nothing to do with the control flow that is regulated by the grammar. If the workflow model is structured, we will “structure” the corresponding STNU.

## 2.4 Temporal RBAC Models

So far, we have not talked about workflow security, but, as we mentioned above, our aim is to put a temporal *Role-Based Access Control (RBAC, [24])* model on top of a workflow model. As the name says, RBAC models rely on the concept of *role*, which is different from that of group, as it is a collection of both users and permissions (thus, it acts as an interface between them), rather than a collection of users only [23]. The main components of an RBAC model are:

- **Users, Roles, Perm, Sess** representing the set of users, roles, permissions and sessions, respectively.
- $UA \subseteq \mathbf{Users} \times \mathbf{Roles}$  and  $PA \subseteq \mathbf{Roles} \times \mathbf{Perm}$  representing many to many user-role and permission-role assignment relations, respectively.
- $user : \mathbf{Sess} \rightarrow \mathbf{Users}$  and  $role : \mathbf{Sess} \rightarrow 2^{\mathbf{Roles}}$  representing functions assigning each session to a single user and to a set of roles, respectively.
- $RH \subseteq \mathbf{Roles} \times \mathbf{Roles}$  representing a partially ordered role hierarchy relation  $\geq$ .

Moreover, in the classical RBAC model a role  $R$  is always **enabled** and can be activated in a session by a user  $u$  such that  $(u, R) \in UA$ . Thus, to deal with the lack of constraints on role enabling and disabling, TRBAC was proposed as a first temporal extension [3]. In this model, a user  $u$  can activate a role  $R$  provided that both he is authorized to do so and the role is **enabled** at the time of the request, i.e.,  $R \in ST(t)$ , where  $ST(t)$  is the set of **enabled** roles at time  $t$ . It follows that the concept of *status*  $\{\mathbf{active}, \mathbf{inactive}\}$  of a role is implicitly augmented by adding  $\{\mathbf{enabled}, \mathbf{disabled}\}$ . Note that, if a role is **active** (i.e., there is an associated user playing it in some session), then it is also **enabled**. In general, the vice versa does not hold.

Roles are **enabled** and **disabled** according to the content of the *role enabling base* (REB)  $\mathcal{R}$ , which mainly consists of periodic events and triggers. A *periodic event* has the form  $(I, P, p : E)$ , where:  $I$  is a time interval,  $P$  is a periodic expression using calendars [20], and  $p : E$  is a prioritized event expression where  $p$  is a priority and  $E$  has the form **enable**  $R$  or **disable**  $R$  for some  $R \in \mathbf{Roles}$ . For example

([01/01/15,  $\infty$ ], WorkingHours, H:enable director)

tells the system to enable (with high priority) the role **director** from 1 January 2015 onwards, as soon as current time gets to the starting point of each interval spanned by **WorkingHours**, which is a periodic expression representing all time instants from 9AM to 1PM and from 2PM to 6PM of week days (i.e., from Monday to Friday).

A *role trigger* has the form  $B \rightarrow p : E$  and its meaning is to fire the periodic event on the right of  $\rightarrow$  whenever all preconditions on the left (the body of the trigger consisting of periodic expressions and role status expressions) become true [3]. A role status expression is either **enabled**  $R$  or **¬enabled**  $R$ . When firing a role trigger these expressions will be evaluated true or false depending on the status of  $R$  at that time. For example, the trigger

**enable** director  $\rightarrow$  **enable** cashier

tells the system to enable the role **cashier** whenever the role **director** gets **enabled**.

In this paper, we consider the fragment of TRBAC consisting of non-conflicting complementary periodic events. For sake of simplicity, we do not consider *non-complementary periodic events* and *conflicting events*. Thus, we assume that each interval spanned by the periodic expression is not influenced by other periodic events. Moreover, we do not consider *runtime request expressions* (and thus *individual exceptions*) because they allow a security officer to override any execution. We also do not consider *role triggers* because they may lead to the previous problems. Thus, under these assumptions, priorities will not influence the behavior of the system.

## 3 Access-controlled Workflows

We first focus on how a controllable workflow can be executed with respect to a given fragment of TRBAC, where the assumptions made at the end of Section 2.4 hold. Then, in Section 3.3 we

derive the set of users authorized to execute a time point. In Section 4, we introduce a running example to discuss a possible real application. In Section 5, we introduce security constraints and related propagation rules to enforce security policies at execution time. In Section 6, we discuss how to execute the access-controlled workflow.

Let us start by supposing that we want to understand whether a controllable workflow can be executed with respect to the considered fragment of TRBAC. In such a model, the set  $\text{Perm} = \{T_1, \dots, T_n\}$  of permissions consists of the workflow tasks, and the interpretation of the role-permission assignment relation  $(R, T) \in PA$  is “all users belonging to  $R$  are authorized to execute task  $T$ ”.

As we have already said, roles are **enabled** during certain time intervals and typically **disabled** in the complementary. Consequently, since a workflow task  $T$  is represented as a contingent link  $A \xrightarrow{[x,y]} C$  where there is no control on the contingent point  $C$ , the interval where the associated role is **enabled** is supposed to be at least as large as the maximal duration of the contingent link, i.e.,  $y$  (otherwise, the workflow would not be consistent with the access control model). Thus, since the workflow and the access control model do not depend on each other, we first need to reduce both models to a common representation to be able to analyze their interplay. To that end, we have chosen to translate the enabling/disabling intervals of roles belonging to the access control model into an equivalent STN to be connected to the STNU representing the workflow model. We proceed as follows: Section 3.1 introduces a mapping to translate such intervals into an equivalent STN, and then Section 3.2 explains how to connect the resulting STN to the workflow-related STNU.

### 3.1 From Periodic Expressions to STNs

Let  $\mathcal{C}_i$  be a calendar (*Hours, Days, Weeks, ...*) and  $\mathcal{C}_i \sqsubseteq \mathcal{C}_j$  be the sub calendar relation (e.g., *Days*  $\sqsubseteq$  *Weeks*). A *periodic expression* has the form  $\sum_{i=1}^n O_i \cdot \mathcal{C}_i \triangleright r \cdot \mathcal{C}_d$ , where  $O_1 = \text{all}$ ,  $O_i \in 2^{\mathbb{N}} \cup \{\text{all}\}$ ,  $\mathcal{C}_i \sqsubseteq \mathcal{C}_{i-1}$  for  $i = 2, \dots, n$ ,  $\mathcal{C}_d \sqsubseteq \mathcal{C}_n$  and  $r \in \mathbb{N}$  [20]. The part on the left of  $\triangleright$  specifies the set of starting points ( $O_i$ s) of the spanned intervals with respect to each calendar ( $\mathcal{C}_i$ ) involved, whereas the part on the right specifies the duration of those intervals in terms of time units ( $r$ ) in the minimum granularity calendar ( $\mathcal{C}_d$ ). For example, assuming that Monday is the first day of every week, **WorkingHours** can be formalized as follows:

$$\text{all} \cdot \text{Weeks} + \{1, 2, 3, 4, 5\} \cdot \text{Days} + \{10, 15\} \cdot \text{Hours} \triangleright \{4\} \cdot \text{Hours}.$$

Periodic expressions implicitly talk about intervals according to the minimum granularity chosen (in this case *Hours*). The  $x^{\text{th}}$  hour of the day starts at time instant  $x - 1$  and ends at  $x$ . For instance, the time instant corresponding to 9AM corresponds to the left bound of the 10<sup>th</sup> hour of the day. Likewise, 1PM corresponds to the right bound of the 4th hour of the first interval spanned by **WorkingHours** starting from the 10<sup>th</sup> (i.e., the 13<sup>th</sup> hour since this interval contains the 10<sup>th</sup>, 11<sup>th</sup>, 12<sup>th</sup>, and 13<sup>th</sup> hour of the day).

Every periodic expression can be translated into an equivalent set of simple periodicity constraints. That is, *linear repeating intervals of integers* along with a *gap constraint* that limits its applicability as described in [2] (which was inspired by [25]). Let  $P$  be a periodic expression,  $\text{Periodicity}(P)$  the number of time units in which  $P$  repeats,  $\text{Granularity}(P)$  the duration of each spanned interval and  $\text{Displacement}(P)$  the set of integers representing the starting points of the spanned intervals. Then, the *set of equivalent linear repeating intervals of integers* is formally represented by:

$$I^P = \{I_{n+1,z}^P \mid 1 \leq y \leq \text{Granularity}(P) \wedge z \in \text{Displacement}(P)\},$$

where each  $I_{n+1,z}^P = [t_1, \dots, t_{\text{Granularity}(P)}]$  represents the  $(n+1)^{\text{th}}$  interval of integers spanned by the periodic expression  $P$  according to the displacement  $z$ , and in turn  $t_1, \dots, t_{\text{Granularity}(P)}$  are generated according to the following equation representing the class of integers

$$t \equiv_{\text{Periodicity}(P)} (y + z - 1),$$

for every  $y \in \{1, \dots, \text{Granularity}(P)\}$  once we have fixed  $z \in \text{Displacement}(P)$  and  $n \in \mathbb{N}$ , where  $t \equiv_k c$  denotes the set of integers of the form  $c + kn$ , ranging from  $-\infty$  to  $+\infty$  in  $\mathbb{Z}$ . For

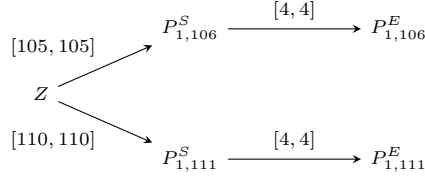


Figure 1:  $\mu_{pt2stn}(\text{WorkingHours}, [05/01/15, 05/01/15])$ .

each  $z \in \text{Displacement}(P)$ , the set of all start and end points of all intervals spanned by  $P$  is computed with respect to  $y = 1$  and  $y = \text{Granularity}(P)$ , respectively.

For example, consider the first complete week of 2015 only (i.e., that starting on 5 January). **WorkingHours** translates to  $t \equiv_{168} (y + z - 1)$  for  $y = 1, 2, 3, 4$  and  $z = 106, 111, 130, 135, 154, 159, 178, 183, 202, 207$ , i.e., from the 10<sup>th</sup> and the 15<sup>th</sup> hour from Monday to Friday of that week for 4 hours.

To get time intervals of real instants, we modify this translation so that it computes directly such intervals considering only the left and the right bounds. In other words, given  $P$  and an interval  $I = [\text{begin}, \text{end}]$  where **begin**, **end** are two date expressions identifying a specific granule according to the minimal granularity adopted<sup>1</sup> and  $0 \leq \text{begin} \leq \text{end} < \infty$ , the resulting intervals  $I_{n+1,z}^P$  can be computed as  $t \equiv_{168} (y + z - 1)$  for  $y = 0, 4$  by fixing each time the value of  $n \in \mathbb{N}$  and  $z$  as before (where 168 is the number of hours in a week). Depending on the chosen  $z \in \text{Displacement}(P)$ , and for  $p = \text{Periodicity}(P)$  and  $g = \text{Granularity}(P)$ , intervals have thus the form

$$[pn + z - 1, pn + z - 1 + g]$$

that instantiated for our **WorkingHours** becomes

$$[168n + z - 1, 168n + z + 3].$$

For instance, if we restrict the applicability of  $P$  to  $I = [05/01/15, 05/01/15]^2$  (i.e., the first Monday of 2015), then we will obtain:

$$\begin{aligned} & \overbrace{[106, 107, 108, 109]}^{05/01/15, (9\text{AM}-1\text{PM})} \cup \overbrace{[111, 112, 113, 114]}^{05/01/15, (2\text{PM}-6\text{PM})} \\ &= 105 \leq t \leq 109 \cup 110 \leq t \leq 114 \end{aligned}$$

where the first line is the computation of linear repeating intervals of integers, and the second one the conversion in intervals of real time instants.

Once we have translated  $P$  in a finite number of intervals of real values representing the intervals spanned by  $P$  itself, we can generate an equivalent STN representing them. We will refer to this mapping  $\mu_{pt2stn} : P \times I \rightarrow \langle \mathcal{T}, \mathcal{C} \rangle$  as *periodic time to STN*. Note that for an STN to be generated it is important that the upper bound of the interval limiting the applicability of the expression  $P$  is  $\neq \infty$ . Thus, the resulting STN is represented in Figure 1.

**Theorem 1** *Given any periodic expression  $P$  whose applicability is limited by an interval  $I$  whose upper bound is  $\neq \infty$ , the mapping  $\mu_{pt2stn}$  returns an equivalent STN that is (i) consistent and (ii) admits exactly one solution.*

The proof is given in the appendix. As a convention, when we write  $P_{n+1,z}^{sup}$  we mean the start (if *sup* is *S*) or the end (if *sup* is *E*) point of the  $(n+1)^{\text{th}}$  ( $n \in \mathbb{N}$ ) interval spanned by  $P$  choosing the displacement  $z$  according to the mapping  $\mu_{pt2stn}$ .

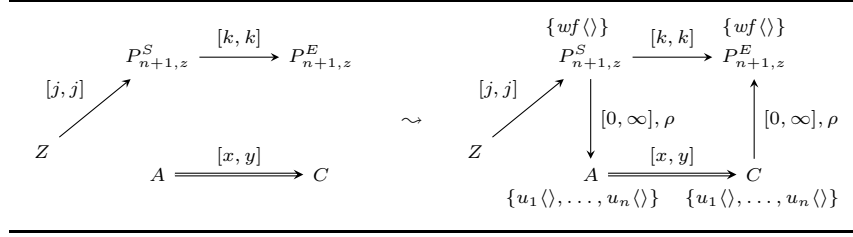
Since the TRBAC periodic events we consider are *non-conflicting* and *complementary*, applying the mapping  $\mu_{pt2stn}$  on the bounded periodic expressions associated to the periodic events involving only an “**enable R**” entails that for each  $n$  and  $z$ ,  $P_{n+1,z}^S \rightarrow P_{n+1,z}^E$  represents a time

<sup>1</sup>In this case, a date expression has the form **dd/mm/yy:hh** where **hh** identifies the (**hh**)<sup>th</sup> hour of **dd/mm/yy**.

<sup>2</sup>When we write  $[\text{dd}_1/\text{mm}_1/\text{yy}_1, \text{dd}_2/\text{mm}_2/\text{yy}_2]$  we mean that **hh**<sub>1</sub> = 01 whereas **hh**<sub>2</sub> = 24.



Table 2: Connection mapping.



interval (of fixed duration) in which the roles associated to this expression in the TRBAC role enabling base  $\mathcal{R}$  are **enabled**. Furthermore, it also turns out that the complementary intervals have the form  $[P_{n+1,z}^E, P_{n+2,z}^S]$ , where the bounds correspond to the real values given by the scheduler  $\psi : \mathcal{T} \rightarrow \mathbb{R}$  (which always assigns the same fixed values to these points depending on  $n$  and  $z$  and  $P$ ). The next subsection explains how an STN generated by the mapping  $\mu_{pt2stn}$  restricted to a given upper bound can be connected to the STNU describing the workflow to check if the workflow itself can be executed with respect to the given access control model. We point out that, in general, the mapping  $\mu_{pt2stn}$  returns different STNs depending on the time window we consider (where a time window is, e.g., the first complete day of the current year, or the 2nd complete week of the 3rd month of the next year). Keeping this flexibility allows us to analyze the access control model in different time windows to leave room for investigating whether or not a workflow is controllable for all possible STNs generated by  $\mu_{pt2stn}$ .

### 3.2 Connecting the Access Control Model

We are now ready to explain how we can put an access control model on top of a workflow by connecting the STN describing the access control model to the STNU describing the workflow. When we connect these two networks we say that the resulting network, which is still an STNU, is a *configuration*.

Assume a workflow consists of  $n$  tasks  $T_1, \dots, T_n$  corresponding to the  $n$  contingent links  $A_1 \Rightarrow C_1, \dots, A_n \Rightarrow C_n$  in the workflow STNU. Also, assume the role  $R$  is authorized to execute the task  $T$  (i.e.,  $(R, T) \in PA$ ) during the time interval  $I_{n+1,z}^P = [P_{n+1,z}^S, P_{n+1,z}^E]$  represented by the requirement link  $P_{n+1,z}^S \xrightarrow{[k,k]} P_{n+1,z}^E$ , for some  $P, n, z$  and  $k = P_{n+1,z}^E - P_{n+1,z}^S$ . Then, to get a configuration we need to impose that the start of  $T$  has to occur *after*  $P_{n+1,z}^S$ , whereas the end *before*  $P_{n+1,z}^E$ .

In other words, role  $R$  cannot start  $T$  before getting **enabled**, and cannot end it after getting **disabled**. A *connection mapping*  $\mu_{con} : \langle \mathcal{T}, \mathcal{C}, \mathcal{L} \rangle \times \langle \mathcal{T}', \mathcal{C}' \rangle \rightarrow \langle \mathcal{T}'', \mathcal{C}'', \mathcal{L}' \rangle$  is formally depicted in Table 2, where on the left the STN representing the access control (above) and the STNU representing the workflow (below) are still not connected, whereas on the right they are. Also, note that we have added a new label  $\rho$  on the links connecting the STN to STNU. In general, this new label  $\rho = R_1 R_2 \dots R_n$  consists of a conjunction of roles saying which roles we want to consider during the interval in which they are **enabled** (as more roles can be **enabled** during the same interval).

**Lemma 1** *Given a task represented as a contingent link  $A \xrightarrow{[x,y]} C$  connected to a requirement link of access control STN  $P_{n+1,z}^S \xrightarrow{[k,k]} P_{n+1,z}^E$  by means of the connection mapping  $\mu_{con}$  shown in Table 2, then if  $k < y$  the resulting STNU is uncontrollable.*

The proof is given in the appendix.

### 3.3 Deriving Authorized Users

Once we have connected the two networks, we are able to derive new information on which are the users authorized to execute the time points. To represent this piece of information, we

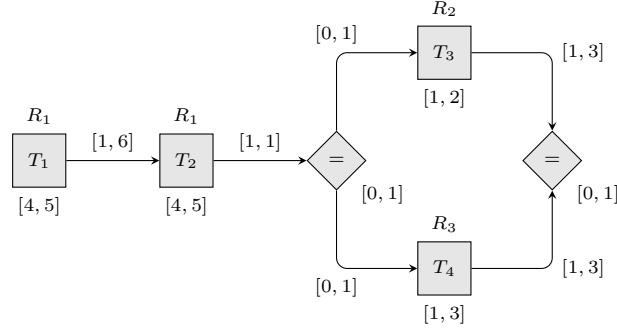


Figure 2: Access-controlled workflow. Tasks  $T_1$ ,  $T_2$ ,  $T_3$ ,  $T_4$  stand for **OutwardJourney**, **ReturnJourney**, **SystemCheck** and **SecurityCheck**, respectively. Roles  $R_1$ ,  $R_2$ ,  $R_3$  stand for *TrainDriver*, *SystemEngineer* and *SecurityEngineer*, respectively.

associate to each time point  $X \in \mathcal{T}$  the set  $\mathcal{A}(X) \subseteq \mathbf{Users}$  of users authorized to execute it as follows.

- For each contingent link  $A \Rightarrow C$  representing task  $T$ , the set of authorized users is  $\mathcal{A}(A) = \mathcal{A}(C) = \{u_1\langle c_1 \rangle, \dots, u_n\langle c_n \rangle\}$ , where  $c_1, \dots, c_n$  are security constraints we define in Section 5 and  $u_1, \dots, u_n$  are users belonging to all roles  $R_i$  such that:
  1.  $(R_i, T) \in PA \wedge (u_i, R_i) \in UA$  for  $j = 1, \dots, n$  (in the TRBAC model), and
  2.  $R_i$  belongs to  $\rho$  specified on the requirement links connecting  $P_{n+1,z}^S$  to  $A$  and  $C$  to  $P_{n+1,z}^E$ , where  $P$  is the associated periodic expression in the periodic event enabling  $R_i$  in the REB  $\mathcal{R}$ .
- For each other time point  $X$  different from an activation or a contingent point,  $\mathcal{A}(X) = \{wf\langle \rangle\}$  which is a special user we consider to advance the execution of “internal tasks” (e.g., branching points). To be more precise we assume that: (i)  $wf \in \mathbf{Users}$ , (ii) for all  $R \in \mathbf{Roles}$ ,  $(wf, R) \notin UA$ , (iii) for all  $X \neq A$  and  $X \neq C$ ,  $wf\langle \rangle \in \mathcal{A}(X)$ , and (iv) for all  $X \equiv A$  or  $X \equiv C$ ,  $wf\langle c \rangle \notin \mathcal{A}(X)$ .

To conclude this section we extend the form of the classical solution  $\mathbf{S} = \{X = t_X, \dots\}$  of a network to the new one  $\mathbf{S} = \{(u_i : X = t_X), \dots\}$  for it to take into account who has executed the time point. The contingency is modeled by the fact that once a task has started we do not know when exactly the user will tell the system that he has finished. Of course, we assume the user to finish within the bounds imposed by the contingent link, otherwise the system raises an exception to cope with the situation.

## 4 Case study

Before we discuss *how* to enforce security policies at runtime, we introduce a running example.

### 4.1 Workflow

We consider a workflow modeling a round-trip from London to Edinburgh. It starts with the task **OutwardJourney** in which the train travels from London to Edinburgh. The journey takes from 4 to 5 hours to be completed. After the train has arrived to Edinburgh train station, the **ReturnJourney** to London starts within 5 hours since 1 hour after arrival. Once the train has returned, before the next round trip starts, a **SecurityCheck** and a **SystemCheck** are done in parallel. The first check takes 1 to 2 hours, the second 1 to 3 hours. Figure 2 shows the workflow consisting of 4 tasks, where we have used the graphical components specified in Table 1 (on the left) and decorated each task by a label that specifies the role authorized to carry it out.

$\mathcal{R}$
$PE_1 : ([01/01/15, \infty], P_1, \text{enable } TrainDriver)$
$PE_2 : ([01/01/15, \infty], P_2, \text{enable } SystemEngineer)$
$PE_3 : ([01/01/15, \infty], P_3, \text{enable } SecurityEngineer)$

Figure 3: The Role Enabling Base of the case study.

## 4.2 Access Control

The instantiation of the TRBAC is as follows:

- **Users** = {*Alice, Bob, Charlie, Eve, Kate*}
- **Roles** = {*TrainDriver, SystemEngineer, SecurityEngineer*}
- **Perm** = {*OutwardJourney, ReturnJourney, SystemCheck, SecurityCheck*}
- **UA** = {(*Alice, TrainDriver*), (*Bob, TrainDriver*), (*Charlie, SystemEngineer*), (*Charlie, SecurityEngineer*), (*Eve, SecurityEngineer*), (*Kate, SystemEngineer*)}
- **PA** = {(*TrainDriver, OutwardJourney*), (*TrainDriver, ReturnJourney*), (*SystemEngineer, SystemCheck*), (*SecurityEngineer, SecurityCheck*)}

The role enabling base  $\mathcal{R}$  (Figure 3) consists of periodic events only. Each line represents a periodic event as described in Section 2.4, where the periodic expressions associated to the roles<sup>3</sup> are:

- $P_1 = all \cdot Days + \{9\} \cdot Hours \triangleright \{12\} \cdot Hours$
- $P_2 = all \cdot Days + \{16\} \cdot Hours \triangleright \{9\} \cdot Hours$
- $P_3 = all \cdot Days + \{16\} \cdot Hours \triangleright \{12\} \cdot Hours$

In other words, these periodic expressions say that the role *TrainDriver* is enabled every day from 8AM to 8PM, *SystemEngineer* every day from 3PM to 12AM (midnight) and *SecurityEngineer* from 3PM until 3AM of the day after. Now consider the time window [01/01/15:01, 02/01/15:03] limiting  $P_1, P_2$  and  $P_3$ . Role *TrainDriver* is enabled during [8, 20], *SystemEngineer* during [15, 24] and *SecurityEngineer* during [15, 27]. Figure 4 shows the resulting configuration.

## 4.3 (Temporal) Security Policies

To conclude the case study section we formalize three security policies that are supposed to hold in this context.

**Security Policy 1** A user who starts a task ends it too.

**Security Policy 2** A user is allowed to execute no more than one task at a time.

**Security Policy 3** If the train driver from Edinburgh to London is the same as the one who drove the train from London to Edinburgh, he must rest at least 2 hours before driving again.

We assume that policies 1, 2 and 3 hold for our case study.

Without security constraint propagation rules, it is rather easy to note that, if every time we start or end a task we are free to choose any authorized user among those contained in that set, then our example violates all the previous security policies. Therefore, the next section provides a language to define security constraints along with a set of security constraint propagation rules to propagate them when executing.

<sup>3</sup>We assume  $\mathcal{R}$  also contains the complementary expressions to disable the roles.

## 5 Propagation of Security Constraints

In Section 3.3, we discussed how to compute the set of authorized users for a time point once we have obtained a configuration (Section 3.2). We now proceed by giving its canonical form as further contribution.

**Definition 3** For each time point  $X$  belonging to a configuration, the set of authorized users has the *canonical form*  $\mathcal{A}(X) = \{u_1\langle c_1 \rangle, u_2\langle c_2 \rangle, \dots, u_n\langle c_n \rangle\}$ , where  $u_1, \dots, u_n$  are the authorized users and  $c_1, \dots, c_n$  are (temporal) security constraints defined according to the grammar

$$\begin{aligned} c &::= t_k, \square \mid X + k, \square \\ \square &::= > \mid < \mid \geq \mid \leq \mid = \mid \neq \end{aligned}$$

where  $t_k, k \in \mathbb{R}^{\geq 0}$ .  $c = t_k, \square$  is a *Type-1 security constraint*, whereas  $c = X + k, \square$  is *Type-2*.

Every Type-2 security constraint  $c = X + k, \square$  is reducible to a Type-1 by substituting  $X$  with a real value taken from its range, plus  $k$  (if  $k \neq 0$ ). As an example, let  $c = X + 1, \leq$ . Once the value of  $X$  becomes known, say the scheduler executes it at time 3 ( $\psi(X) = 3$ ), we substitute it for  $X$  also adding the constant  $k = 1$ . After that, the Type-2 security constraint reduces to the Type-1  $c' = 4, \leq$ .

$$\underbrace{c = X + 1, \leq}_{t < 3} \xrightarrow{\psi(X)=3} \underbrace{c' = 4, \leq}_{t \geq 3}$$

The main idea behind a security constraint is that of blocking the associated user in order to prevent him from executing some time point if a security policy is violated.

**Definition 4** We define *interpretation* of security constraints with respect to current time  $t$  as follows:

- |   |                                |
|---|--------------------------------|
| 1. $t \models t_k, >$ iff $t > t_k$       | 7. $t \not\models X + k, >$    |
| 2. $t \models t_k, <$ iff $t < t_k$       | 8. $t \models X + k, <$        |
| 3. $t \models t_k, \geq$ iff $t \geq t_k$ | 9. $t \not\models X + k, \geq$ |
| 4. $t \models t_k, \leq$ iff $t \leq t_k$ | 10. $t \models X + k, \leq$    |
| 5. $t \models t_k, =$ iff $t = t_k$       | 11. $t \not\models X + k, =$   |
| 6. $t \models t_k, \neq$ iff $t \neq t_k$ | 12. $t \models X + k, \neq$    |

A user  $u$  is *blocked* for the time point  $X$  if  $u\langle c \rangle \in \mathcal{A}(X)$ , and current time  $t \models c$ .

It is clear from the context that 1–6 regard Type-1 security constraints, whereas 7–12 regard the Type-2. The interpretation of the first group with respect to the chosen  $\square$  operator substantially states that those constraints will be true if current time  $t$  is greater than the value specified (1), less than it (2), greater than or equal to it (3), less than or equal to it (4), equal to it (5), or different from it (6). Instead, that of the second group (Type-2) is a little bit subtle since the value of time point specified in it is still unknown.

The interpretation with respect to the chosen  $\square$  operator states that, since  $X$  will be executed in the future and is thus yet unknown, the Type-2 constraint is interpreted false (7), true (8), false (9), true (10), false (11) and true (12). When  $X$  executes the Type-2 constraint is reduced to a Type-1 and interpreted accordingly.

As an example, consider  $c = X + 3, >$ . The current time satisfies this constraint iff it is greater than  $X + 3$ , where the value of  $X$  is still unknown. Therefore, at current time  $t$  this constraint is false.

Furthermore, when  $X$  executes, this constraint remains false for 3 other time units. Now consider the complementary case  $c = X + 3, \leq$ . The current time satisfies  $c$  iff it is less than or equal to  $X + 3$ , where the value of  $X$  is still unknown. Even if  $X$  is still unknown, this constraint at time  $t$  is trivially true since current time is of course less than (or equal to) some other value in the future plus some *positive* constant. Furthermore, when  $X$  executes, this

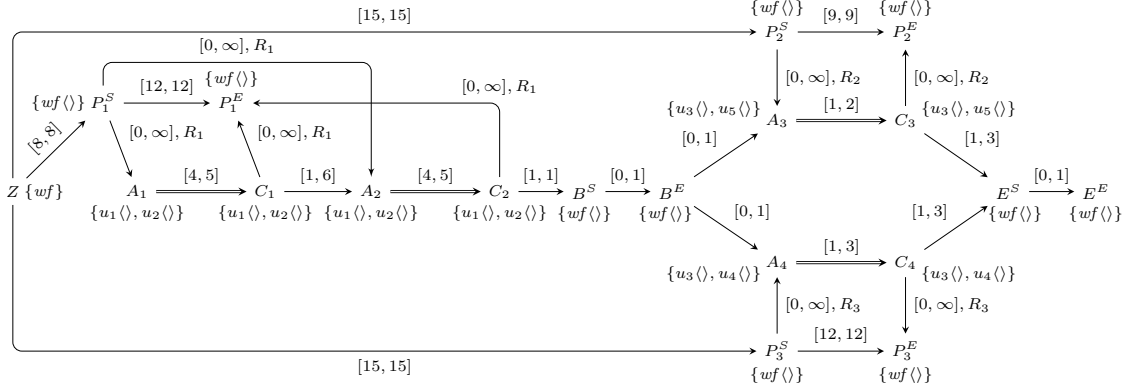


Figure 4: STNU equivalent to the access-controlled workflow depicted in Figure 2. Users  $u_1$ ,  $u_2$ ,  $u_3$ ,  $u_4$ ,  $u_5$  represent *Alice*, *Bob*, *Charlie*, *Eve*, and *Kate*, respectively.

constraint remains true for 3 other time units. Similar explanations apply to the other Type-2 constraints.

Security constraint propagation rules say how security constraints propagate when executing.

**Definition 5** A *security constraint propagation rule (SCPR)* is a 4-tuple of the form:

$$\langle X, \langle c \rangle, \mathcal{Y}, \diamond \rangle$$

where  $X$  is a time point,  $c$  a security constraint,  $\mathcal{Y}$  a set of time points, and  $\diamond$  is either  $=$  or  $\neq$ .

The semantics of an SCPR says that when  $X$  is executed, the security constraint  $c$  has to be set to all users in  $\mathcal{A}(Y)$  ( $Y \in \mathcal{Y}$ ) equal to (if  $\diamond$  is  $=$ ) or different from (if  $\diamond$  is  $\neq$ ) the user who executed  $X$ .

## 5.1 From Security Policies to SCPRs

We can use SCPRs as a means to embed the (temporal) security policies we want to hold. We exemplify this at hand of the three security policies defined in Section 4.3 by sketching a few constructs of an high-level language to define security policies for the workflow we are currently designing. This language allows Security Officers to specify security policies in an easier way without even mentioning time points. Then, an intermediate step is that of generating a set  $S$  of SCPRs starting from the constructs of this language for the system to be able to do a safeness check first and propagate SCs while executing.

We know that by means of the mapping  $\mu_{pt2stn}$  each task  $T$  is represented as a contingent link describing its start and end point. Thus we need constructs such as **start**( $T$ ) and **end**( $T$ ) to model these aspects.

To express conditions on who did what, we envision to have primitives like **hasExecuted**( $u, T$ ), **hasStarted**( $u, T$ ), **hasEnded**( $u, T$ ) as binary predicates modeling the fact that user  $u$  has executed/started/ended task  $T$ .

Instead, to model who is not allowed to start or end a task we envision to have primitives **cannotStart**( $u, T$ ), **cannotEnd**( $u, T$ ) as well as clauses such as  $u_1 = u_2$  and  $u_1 \neq u_2$  (resp.  $T_1 = T_2$  and  $T_1 \neq T_2$ ) to intend the same or a different user (resp. task).

This language also needs to quantify over the sets of authorized users and tasks to formalize properties such as **for all ... [in ...]** other than conditional blocks such as **if ... then ... [else ...]**. Note that since we are considering structured workflows, we are able to formalize statements such as “for all tasks in the first parallel block”.

Last but not least, we need “temporal constructs” such as **before  $k$  after end**( $T$ ) to model security properties such as Temporal Separation of Duties (TSoD).

*Security Policy 1* requires that an authorized user who starts a task ends it too. In the high-level language we expect to formalize it this way:

```

for all  $T$  if hasStarted( $u, T$ ) then
  for all  $u'$  in  $\mathcal{A}(T)$ 
    if  $u' \neq u$  then cannotEnd( $u', T$ )

```

This rule is translated in  $n$  SCPRs having the form:

$$r_i : \langle A_i, \langle C_i, \leq \rangle, C_i, \neq \rangle$$

where  $n$  is the number of tasks which the workflow consists of. In our case study is translated to 4 rules (since the workflow of Figure 2 consists of 4 tasks):

$$\begin{aligned}
r_1 &: \langle A_1, \langle C_1, \leq \rangle, C_1, \neq \rangle & r_3 &: \langle A_3, \langle C_3, \leq \rangle, C_3, \neq \rangle \\
r_2 &: \langle A_2, \langle C_2, \leq \rangle, C_2, \neq \rangle & r_4 &: \langle A_4, \langle C_4, \leq \rangle, C_4, \neq \rangle
\end{aligned}$$

That is, every time an authorized user  $u$  executes an activation point  $A$ , the system sets the constraint  $C, \leq$  to all users  $u' \in \mathcal{A}(C)$  where  $u' \neq u$ . Those users will be blocked until  $t \models C, \leq$  (i.e., until  $C$  is executed).

*Security Policy 2* requires that an authorized user is allowed to execute one task at a time.

```

for all  $T$  in ParallelBlock if hasStarted( $u, T$ ) then
  for all  $T'$  in ParallelBlock if  $T' \neq T$  then
    cannotStart( $u, T'$ ) before end( $T$ )

```

This rule is translated in  $n$  SCPRs having the form:

$$r_i : \langle A_i, \langle C_i, \leq \rangle, \{A_j\}, = \rangle$$

where  $i \neq j$  and  $n$  is the number of tasks in the considered parallel block (because we model all possible cases). In our case study is translated to:

$$r_5 : \langle A_3, \langle C_3, \leq \rangle, \{A_4\}, = \rangle \quad r_6 : \langle A_4, \langle C_4, \leq \rangle, \{A_3\}, = \rangle$$

In the case study introduced in Section 4 there is only one parallel block which consists of tasks  $T_3, T_4$  (Figure 2) or equivalently contingent links  $A_3 \Rightarrow C_3, A_4 \Rightarrow C_4$  (Figure 4). Therefore, if a user can execute both tasks (where the execution order of  $T_3, T_4$  is not well defined), we must prevent him from executing the other until the current is not finished. Relying on  $r_1$  it is enough to set the constraint (i.e., to block the user) only on the activation points  $A_3, A_4$  depending on which task executes first.

*Security Policy 3* requires that if the same authorized user executes  $T_1$  and  $T_2$ , then between the end of  $T_1$  and the start of  $T_2$  at least 2 hours have to elapse.

```

for all  $u$  in  $\mathcal{A}(T_1)$  if hasStarted( $u, T_1$ ) then
  cannotStart( $u, T_2$ ) before 2 after end( $T_1$ )

```

This rule is translated in a single SCPR having the form:

$$r_i : \langle C_i, \langle C_i + 2, \leq \rangle, \{A_j\}, = \rangle$$

where  $i \neq j$ . In our case study is translated to:

$$r_7 : \langle C_1, \langle C_1 + 2, \leq \rangle, \{A_2\}, = \rangle$$

The same reason of  $r_5, r_6$  (i.e., *relying on*  $r_1$ ) applies here to avoid writing a redundant  $C_2$  in  $r_7$ 's  $\mathcal{Y}$ .

---

**Algorithm 1** A safeness-checker for a set  $S$  of SCPRs

---

```
1: procedure SafenessChecker( $S$ )
2:   for all  $r_1, r_2 \in S$  do
3:     if  $r_1 \neq r_2$  and  $r_1$  and  $r_2$  are conflicting then
4:       return false
5:     end if
6:   end for
7:   return true
8: end procedure
```

---

*Separation of Duties (SoD)* requires that the same user ought not be able to carry out two sensitive tasks in the same execution. *Temporal Separation of Duties (TSoD)* is an extension of SoD that allows the same user to do so, but *only if* a further temporal constraints is satisfied. In our example, the train driver can bring the train back to London as long as he has rested at least 2 hours (the further temporal constraint). Furthermore, imposing this constraint at workflow level (e.g., tightening the STNU by means of a requirement link  $C_1 \xrightarrow{[2+\epsilon, \infty]} A_2$ , for some  $\epsilon > 0$ ) would be wrong. Indeed, it would prevent *all* train drivers different from the one who drove the train during the outward journey from driving the train in the return journey *as soon as possible* since the arrival at Edinburgh station. That is, exactly after 1 hour considering that we have the constraint  $C_1 \xrightarrow{[1, 6]} A_2$  (Figure 4).

## 5.2 Safeness of a set of SCPRs

We are left to specify the notion of *safeness* for a set  $S$  of SCPRs. We recall that an STNU is executed incrementally [17]. To do that, we must define (i) *conflicting rules*, and (ii) an *algorithm* to check if a set  $S$  of SCPRs does not contain any pair of conflicting rules. We proceed by providing the definition of conflicting rules and then a safeness check algorithm.

**Definition 6** Two SCPRs  $r_1 = \langle X_1, c_1, \mathcal{Y}_1, \diamond_1 \rangle$  and  $r_2 = \langle X_2, c_2, \mathcal{Y}_2, \diamond_2 \rangle$  are in *conflict* iff the following four conditions hold all together: (1)  $X_1 = X_2$ , (2)  $c_1 \neq c_2$ , (3)  $\mathcal{Y}_1 \cap \mathcal{Y}_2 \neq \emptyset$ , and (4)  $\diamond_1 = \diamond_2$ .

As an example, the following two SCPRs are conflicting:

$$r_1 : \langle X, \langle Y + 2, \leq \rangle, \{Z, V\}, \neq \rangle \quad r_2 : \langle X, \langle Y, > \rangle, \{W, Z\}, \neq \rangle$$

Rule  $r_1$  says that when  $X$  has been executed by  $u \in \mathcal{A}(X)$  the security constraint  $Y + 2, \leq$  has to be set for all users different from  $u$  belonging to the sets  $\mathcal{A}(Z)$  and  $\mathcal{A}(V)$ , whereas  $r_2$  says that the complementary constraint  $(Y, >)$  has to be set, again, for all users different from  $u$  belonging to  $\mathcal{A}(W)$  and  $\mathcal{A}(Z)$ . These two rules are conflicting since the four conditions hold all together: (1)  $X = X$ , (2)  $Y + 2, \leq \neq Y, >$ , (3)  $\{Z, V\} \cap \{W, Z\} = \{Z\} \neq \emptyset$ , and (4) both  $\diamond$  are  $\neq$ . In other words, they are trying to set *at the same time* a different constraint for the same users belonging to  $\mathcal{A}(Z)$ .

It is quite easy now to see that the set  $S = \{r_1, \dots, r_7\}$  containing the seven SCPRs translating the three security policies of our case study is *safe*, since there does not exist any pair of conflicting rules. A first brute-force procedure to check the safeness of a set  $S = \{r_1, \dots, r_n\}$  of SCPRs is given in Algorithm 1, which takes as input  $S$  and tests the four conditions of Definition 6 for all different pairs of rules  $r_i, r_j \in S$ . The algorithm runs exactly in  $\Theta(|S|^2)$ .

## 6 Workflow Execution

In order to propagate security constraints when the workflow is being executed we are left to do one thing: to specify how SCPRs are taken into account at runtime. To do so, we extend

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**Algorithm 2** A configuration execution algorithm

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1: procedure Executor( $S$ )
2:    $A$  = set of all control points of the network
3:    $t = 0$ 
4:   while  $A \neq \emptyset$  do
5:     Wait for some time point live and enabled  $X \in A$ 
6:     Arbitrary pick a live and enable time point  $X \in A$ 
7:     Arbitrary pick  $u\langle c \rangle \in \mathcal{A}(X)$  such that  $t \not\models c$ 
8:      $S = S \cup (u : X = t)$ 
9:     Propagate all  $\langle X_i, c_i, \mathcal{V}_i, \diamond_i \rangle \in S$  s.t.  $X = X_i$ 
10:    Advance  $t$  propagating all temporal constraints
11:   end while
12: end procedure
```

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the STNU execution algorithm<sup>4</sup> in [17] for it to take as input also a (safe) set of SCPRs that shall be evaluated each time a time point is executed. If the executed time point matches the guard of some rules, then the constraints in them have to be set (thus propagated) before the execution continues according to all we have said so far (Algorithm 2).

Now it is time to be more concrete by writing down how the state of the system evolves during the execution. Of course, there are infinite different ways of executing a workflow since time is dense; consequently, each range  $[x, y]$  where  $x \neq y$  (e.g., those belonging to contingent links) consists of infinite points. For instance, in our case study we have chosen *a possible execution* with the only purpose of showing how security constraints propagate. The execution is given in Table 3 (in the appendix), where cells in bold-face point out the security constraint(s) being applied.

## 7 Related Work

Related work on defining, validating, and enforcing access control policies in workflow contexts can be grouped in four main areas: (i) access control and workflow models, (ii) authorization constraints, (iii) planning, and (iv) run-time execution.

RBAC models [24] are the default choice for many organizations that need to balance security with flexibility. Classical RBAC models are however unable to deal with security policies at user level, such as separation or binding of duties.

In [5], Bertino et al. give a language for defining authorization constraints on role and user assignment to tasks in a workflow. They also provide algorithms for constraint consistency check and task assignment. This proposal assumes the workflow to verify a total order on tasks (i.e., no parallel tasks are allowed). Furthermore, temporal constraints are not investigated.

The Temporal Authorization Base model described in [4] is able to enforce authorization constraints in heterogeneous distributed systems. It allows users to assign periodic authorizations to other users on sets of objects. This model is quite expressive. In order to use it in a workflow context, we conjecture that it would be required to restrict access modes to **execute** and constrain objects to be **tasks**. However, a thorough investigation is needed, as in our context we also need to deal with the temporal aspects related to workflows.

A number of proposals (Wang and Li in [27] and Crampton et al. in [6, 9, 10, 11, 12], to name a few) have addressed the workflow satisfiability problem (WSP) and the resiliency problem. WSP is the problem of assigning tasks to users so that the execution of the access controlled workflow is guaranteed to reach the end, when dealing with authorization constraints that might prevent some user from doing some action in the future. In general, solving WSP requires exponential time, but some of the cited approaches proved (by using parameterized

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<sup>4</sup>The classic algorithm starts by inserting all control points in the set  $A$ . Then, while  $A$  is not empty, it executes incrementally the enabled time points removing them from it and building the solution  $S$ . A time point is *live* if current time lies between its upper and lower bounds, and *enabled* if it is *live* and all time points to be executed before it have already been executed [17]. In the original version [17] the solution has the form  $S = \{X = t_X, \dots\}$ .



complexity and kernelization) that for some workflow instances (those where the number of users equals the number of tasks) the WSP can be solved in polynomial time. In our work, we have not dealt with WSP yet, but only with the satisfaction of temporal constraints. As for current and future work, we are trying to extend our approach to deal with WSP, by refining the classical STNU DC-check to take into account authorization constraints as well. If an STNU passes this check, then we can also generate an execution strategy to execute the workflow (planning phase), being guaranteed to always get to the end by satisfying all constraints.

On the other hand, the *resiliency problem* faces the issue of how to deal with the execution of plans if some authorized users become unavailable, when the workflow is being executed. To the best of our knowledge, no solution to the WSP and to the resiliency problems using temporal networks has been proposed so far and the related temporal aspects of such problems deserve further attention.

Finally, in [21], Paci et al. proposed proposed *RBAC-WS-BPEL*, a role-based access control model for the web services business process execution language *WS-BPEL*. The language is based on XML and does not deal with temporal constraints, which makes it unsuitable for our context.

## 8 Conclusions and Future work

In this paper we focused on the issue of managing in a seamless way role-based access control mechanisms in temporal workflows, where temporal aspects are both in the access control model and in the workflow model. We based our approach on temporal constraint networks. To the best of our knowledge, all of the existing approaches are unsuitable to deal with a workflow having both temporal constraints related to the execution control model and in the access control model.

We have provided mappings to translate a workflow into an equivalent STNU and a time window of TRBAC into an equivalent STN to be connected to STNU describing the workflow. This allowed us to answer the question about whether or not the resulting configuration is executable. Then, we have derived for each time point the set of authorized users and defined security constraints along with their propagation rules in order to set, update and propagate security constraints also discussing safeness and execution issues.

We view this paper as a first step of a more general research work, where we will consider and face the following research directions: considering *conditional STNUs* [14] in order to augment expressiveness to model different workflow paths; allowing the *combination of temporal security constraints* such as  $u\langle c_1 \wedge c_2 \rangle$  or  $u\langle \neg c \rangle$  to express security policies such as “(not) during”; defining a *high-level security policy language*; and considering the *temporal workflow satisfiability problem* (TWSP) (i.e., *controllability with respect to security*), to do an automated validation of security policies with respect to different possible temporal configurations and user assignments.

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## A Example of execution of the case study

Train TR2015 from London to Edinburgh departs at 08:00 AM (from platform 1). The system (*wf*) starts the workflow at 12AM of the 1st of January 2015. That is, it executes the zero time point  $Z$  without propagating any security constraint. The system also executes at 8 o'clock  $P_1^S$  enabling  $R_1$ .

At 8 o'clock Bob ( $u_2$ ), who is a train driver, starts the outward journey from London to Edinburgh. Rule  $r_1$  (enforcing Security Policy 1) constrains *Bob* to be the only user to end the task (i.e. to execute  $C_1$ ) between 12PM and 1PM by applying the security constraint  $C_1, \leq$  for all users apart from him in  $\mathcal{A}(C_1)$  (row 1). Suppose the outward journey takes 4 hours. Thus, *Bob* tells the system the train has arrived at Edinburgh station at midday (row 2). Furthermore, rule  $r_7$  (enforcing Security Policy 3) prevents *Bob* from starting the return journey before current time does not pass 2 o'clock by applying the security constraint  $14, \leq^5$  for him in  $\mathcal{A}(A_2)$  (again, row 2). Meanwhile at 3 o'clock the system starts both  $P_2^S$  and  $P_3^S$  enabling  $R_2$  and  $R_3$ , respectively without applying any security constraint.

Now let us say that Bob starts the return journey at 3 o'clock. Rule  $r_1$  constrains him to finish the journey between 7PM and 8PM. That is,  $C_2, \leq$  is applied for all users apart from him in  $\mathcal{A}(C_2)$  (row 3). Assume this time the return journey takes its maximal duration (5 hours). Since there is no security policy which says something upon the arrival of the return journey there is not any rule  $r$  whose guard is  $C_2$  either (row 4). The system also disables  $R_1$  by executing  $P_1^E$  at the same time.

Assume now the system decides the duration of the branch block starting the parallel (which can be viewed as an internal task) is instantaneous and starts exactly after 1 hour since the train has got back to London. That is, the system executes  $B^S$  and  $B^E$  at 9 o'clock without applying any security constraint.

Suppose now that Charlie ( $u_3$ ) starts the system check at 9PM. Rule  $r_5$  (enforcing Security Policy 2) prevents him from executing the security check until he has finished the current task by applying  $C_3, \leq$  for him in  $\mathcal{A}(A_4)$  (row 5). The motivation is that Charlie is both a System and a Security Engineer, thereby he is authorized to execute both tasks. Furthermore,  $r_3$  fires too by constraining Charlie to be the only one authorized to end the task applying  $\langle C_3, \leq \rangle$  for all users apart from him in  $\mathcal{A}(C_3)$  (again, row 5).

Assume now that while system check is being executed, Eve ( $u_4$ ) starts the security check at 10PM. Rule  $r_6$  does the same of  $r_5$  but with respect to Eve and task **SystemCheck**. However, since Eve is not a System Engineer (consequently  $u_4 \notin \mathcal{A}(A_3)$ ) this rule has no effect on the state of the system (row 6). Instead,  $r_4$  applies as usual by setting  $C_4, \leq$  for all users apart from Eve in  $\mathcal{A}(C_4)$  (again, row 6). Now suppose Charlie and Eve terminate the tasks they are executing at 11PM and at 1AM (of the day after), respectively (rows 7 and 8). What happens next is that no security constraint is applied (because there are no rules whose guards contain  $C_3$  or  $C_4$ ) and the system disables  $R_3$  at midnight (by executing  $P_2^E$ ) and  $R_4$  at 3AM of the day after (by executing  $P_3^E$ ).

Finally, as for the branch block, the system decides the duration of the join block is instantaneous and starts after 1 hour since the last task (**SecurityCheck** in this strategy) has terminated, i.e., the system executes  $E^S$  and  $E^E$  at 1AM of the day after without applying any security constraint.

Table 3: Example of execution of the case study.  $\mathcal{A}(A_i)$  (resp.,  $\mathcal{A}(C_i)$ ) is the set of users authorized to start (resp., end) task  $T_i$ . The first column shows when which user has executed which time point.

Executed TP	$\mathcal{A}(A_1)$	$\mathcal{A}(C_1)$	$\mathcal{A}(A_2)$	$\mathcal{A}(C_2)$	$\mathcal{A}(A_3)$	$\mathcal{A}(C_3)$	$\mathcal{A}(A_4)$	$\mathcal{A}(C_4)$			
$(wf : Z = 0)$	$\{u_1(), u_2()\}$	$\{u_1(), u_2()\}$	$\{u_1(), u_2()\}$	$\{u_1(), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(wf : P_1^S = 8)$	$\{u_1(), u_2()\}$	$\{u_1(), u_2()\}$	$\{u_1(), u_2()\}$	$\{u_1(), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(u_2 : A_1 = 9)$	$\{u_1(), u_2()\}$	$\{u_1(C_1, \leq), u_2()\}$	$\{u_1(), u_2()\}$	$\{u_1(), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(u_2 : C_1 = 12)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(wf : P_2^S = 15)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(wf : P_3^S = 15)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(u_2 : A_2 = 15)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(C_2, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(u_2 : C_2 = 20)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(wf : P_4^S = 20)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(wf : B^S = 21)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(wf : B^E = 21)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_4()\}$	$\{u_3(), u_4()\}$			
$(u_3 : A_3 = 22)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5(C_3, \leq)\}$	$\{u_3(C_3, \leq), u_4()\}$	$\{u_3(), u_4()\}$			
$(u_4 : A_4 = 22)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5(C_3, \leq)\}$	$\{u_3(C_3, \leq), u_4()\}$	$\{u_3(), u_4(C_4, \leq)\}$			
$(u_3 : C_3 = 23)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5(23, \leq)\}$	$\{u_3(23, \leq), u_4()\}$	$\{u_3(), u_4(C_4, \leq)\}$			
$(wf : P_2^E = 24)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5(23, \leq)\}$	$\{u_3(23, \leq), u_4()\}$	$\{u_3(), u_4(C_4, \leq)\}$			
$(u_4 : C_4 = 25)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5(23, \leq)\}$	$\{u_3(23, \leq), u_4()\}$	$\{u_3(), u_4(25, \leq)\}$			
$(wf : E^S = 26)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5(23, \leq)\}$	$\{u_3(23, \leq), u_4()\}$	$\{u_3(), u_4(25, \leq)\}$			
$(wf : E^E = 26)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5(23, \leq)\}$	$\{u_3(23, \leq), u_4()\}$	$\{u_3(), u_4(25, \leq)\}$			
$(wf : P_3^E = 27)$	$\{u_1(), u_2()\}$	$\{u_1(12, \leq), u_2()\}$	$\{u_1(), u_2(14, \leq)\}$	$\{u_1(20, \leq), u_2()\}$	$\{u_3(), u_5()\}$	$\{u_3(), u_5(23, \leq)\}$	$\{u_3(23, \leq), u_4()\}$	$\{u_3(), u_4(25, \leq)\}$			
Executed TP (cont.)	$\mathcal{A}(Z)$	$\mathcal{A}(P_1^S)$	$\mathcal{A}(P_1^E)$	$\mathcal{A}(P_2^S)$	$\mathcal{A}(P_2^E)$	$\mathcal{A}(P_3^S)$	$\mathcal{A}(P_3^E)$	$\mathcal{A}(B^S)$	$\mathcal{A}(B^E)$	$\mathcal{A}(E^S)$	$\mathcal{A}(E^E)$
$(wf : Z = 0)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : P_1^S = 8)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(u_2 : A_1 = 9)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(u_2 : C_1 = 12)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : P_2^S = 15)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : P_3^S = 15)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(u_2 : A_2 = 15)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(u_2 : C_2 = 20)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : P_4^S = 20)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : B^S = 21)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : B^E = 21)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(u_3 : A_3 = 22)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(u_4 : A_4 = 22)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(u_3 : C_3 = 23)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : P_2^E = 24)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(u_4 : C_4 = 25)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : E^S = 26)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : E^E = 26)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$
$(wf : P_3^E = 27)$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$	$\{wf()\}$

## B Proofs

**Proof 1 (Lemma 1)** Consider an STNU fragment consisting of one contingent link  $A \xrightarrow{[x,y]} C$  connected to a requirement link  $P_{n+1,z}^S \xrightarrow{[k,k]} P_{n+1,z}^E$  by means of the mapping given in Table 2 for some chosen  $P$ ,  $n \in \mathbb{N}$  and  $z \in \text{Displacement}(P)$ . Also, we know that  $k = \text{Granularity}(P)$  and  $k < y$  (by assumption). The STNU fragment along with its labeled distance graph are depicted in Figure 5a and Figure 5b, respectively.

The controllability algorithm [18] iteratively checks for the consistency of the labeled distance graph AllMax projection. This projection must remain consistent during the whole execution which in every cycle adds new edges to the labeled distance graph according to its edge generations rules to make explicit the restriction to the execution strategies [18]. If the AllMax projection survives (i.e., if it remains consistent once the algorithm has terminated), then the STNU is dynamically controllable.

To get the AllMax projection (Figure 5c), we simply remove from the labeled distance graph all the lower-case edges and all the upper-case labels from the upper-case ones. Of course, this projection represents the situation in which the contingent links take their maximum duration (in this case,  $\omega = (y)$ ). Moreover, since by definition the range  $[x, y]$  of each contingent link  $A \Rightarrow C$  respects  $0 < x < y < \infty$ , it follows that  $-y < -x$ . Thus, since in the AllMax projection we have both  $C \xrightarrow{-x} A$  and  $C \xrightarrow{-y} A$ , and we know that  $-y$  is tighter than  $-x$ , we just keep  $C \xrightarrow{-y} A$ .

Now, we know by assumption that  $k < y$ . It turns out that the cycle  $P_{n+1,z}^S \xrightarrow{k} P_{n+1,z}^E \xrightarrow{0} C \xrightarrow{-y} A \xrightarrow{0} P_{n+1,z}^S$  has negative weight that is initially detected by the consistency checking

<sup>5</sup>Instead of applying  $C_1 + 2, \leq$  (as formalized in  $r_1$ ), the system applies directly  $14, \leq$  since the value of  $C_1$  (12) is known.

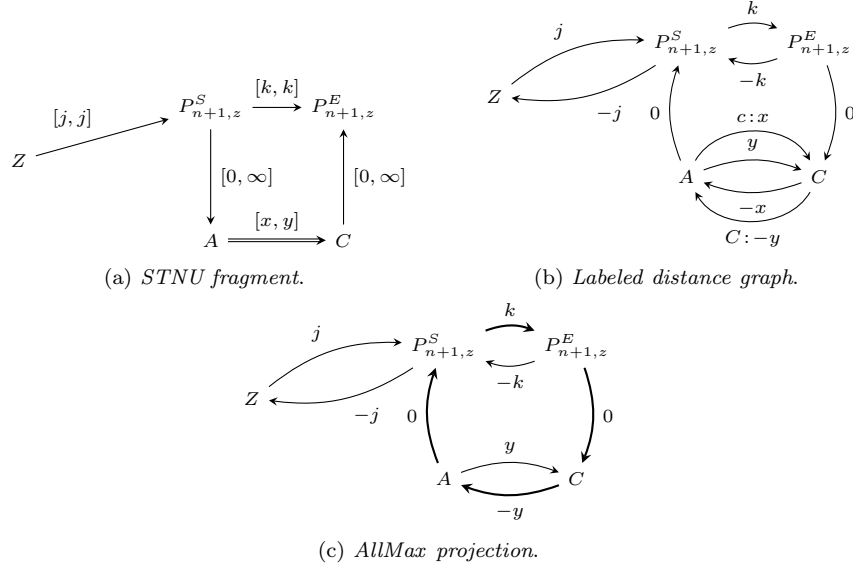


Figure 5: Supporting figures for the proof of Lemma 1.

(carried out by Johnson's algorithm [8]) that computing the all pairs shortest paths algorithm answers the question of whether or not the AllMax projection is consistent. If it is not (as in this case), the algorithm has failed. Consequently, the initial STNU is not dynamically controllable because the inconsistency of AllMax projection excludes weak controllability, which in turn, excludes dynamic controllability [26].

**Proof 2 (Theorem 1)** The mapping  $\mu_{pt2stn} : P \times I \rightarrow \langle \mathcal{T}, \mathcal{C} \rangle$  returns an STN starting from a periodic expression  $P$  whose applicability is limited by an interval  $I$  whose upper bound is  $\neq \infty$ . Thus, for each generated interval  $I_{n+1,z}^P = [t_1, \dots, t_g]$  of integers (where  $g = \text{Granularity}(P)$ ) the equivalent interval of real values is  $[t_1 - 1, t_g]$  which is modeled in the STN as an equivalent requirement link  $P_{n+1,z}^S \xrightarrow{[k,k]} P_{n+1,z}^E$  where  $k = t_g - (t_1 - 1)$  ( $k \geq 0$ ). In addition, all of these requirement links are connected to the source node  $Z$  (zero-time point)  $Z \xrightarrow{[j,j]} P_{n+1,z}^S$  where  $j = t_1 - 1$  ( $j \geq 0$ ). Thus, for all  $n, z$  such that  $I_{n+1,z}^P \subseteq I$ , this mapping builds the STN in Figure 6a.

We are now ready to prove that the resulting STN is (i) consistent, and (ii) admits exactly one solution.

(i) To prove that the resulting STN is consistent we consider its distance graph depicted in Figure 6b.

Let  $w : E \rightarrow \mathbb{R}$  be the weight function that maps each edge  $(u, v) \in E$  to a real value in  $\mathbb{R}$ . Thus, for each pair of connected nodes  $u, v$  we know that  $w(u, v) = -w(v, u)$  (as each range of each time point has the form  $[x, x]$ ). Thus, the weight of the cycle  $u \rightarrow v \rightarrow u$  is  $w(u, v) - w(v, u) = 0$ . It is quite simple to see that if each cycle between two connected nodes has weight 0, so does any other cycle involving  $n > 2$  nodes. It turns out, that there does not exist any cycle whose weight is negative, thus the STN is consistent because the all pairs shortest paths algorithm terminates correctly.

(ii) The reason why the STN admits one and only one solution is due to the fact that for each pair of connected nodes  $u, v$  we know that  $w(u, v) = -w(v, u)$ . Consequently, the weight of each path from a source node  $s$  to any other node  $u$  is equal to the negation of that going from  $u$  to  $s$ . From [13] we know that the weight of the shortest path from  $s$  to  $u$  is the upper bound of the range of allowed values for the time point  $u$ , whereas the negation of the opposite direction (i.e., of the shortest path from  $u$  to  $s$ ) corresponds to the lower bound. When these two values are equal (note that we negate the negation of the path from  $u$  to  $s$ ), then the range of the allowed values for time point  $u$  collapses to only one point. When this holds for all time

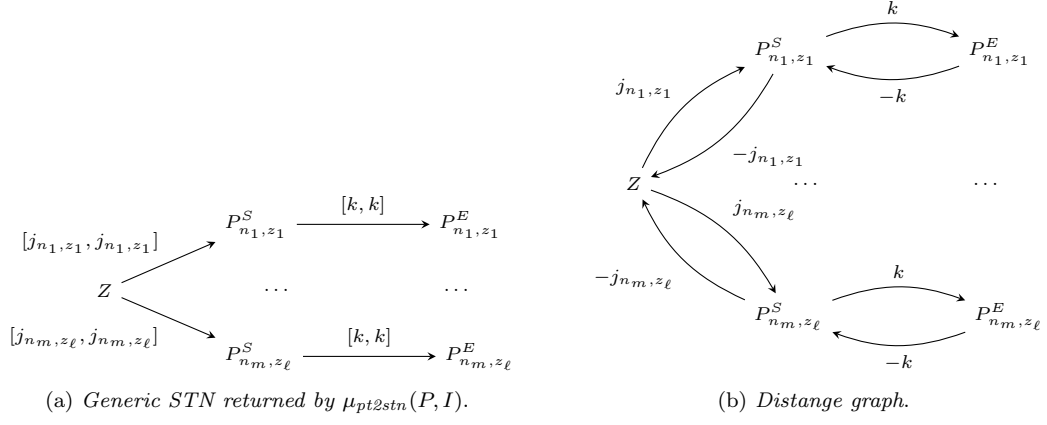


Figure 6: Supporting figures for the proof of Theorem 1.

points, the STN has exactly one solution since the range of allowed values of each time point consists of one possible value only.